

Generalized Secure Transmission Protocol for Flexible Load-Balance Control with Cooperative Relays in Two-Hop Wireless Networks

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Abstract—This work considers secure transmission protocol for flexible load-balance control in two-hop relay wireless networks without the information of both eavesdropper channels and locations. The available secure transmission protocols via relay cooperation in physical layer secrecy framework cannot provide a flexible load-balance control, which may significantly limit their application scopes. This paper extends the conventional works and proposes a general transmission protocol with considering load-balance control, in which the relay is randomly selected from the first k preferable assistant relays located in the circle area with the radius r and the center at the middle between source and destination (2HR- (r, k) for short). This protocol covers the available works as special cases, like ones with the optimal relay selection ($r = \infty, k = 1$) and with the random relay selection ($r = \infty, k = n$ i.e. the number of system nodes) in the case of equal path-loss, ones with relay selected from relay selection region ($r \in (0, \infty), k = 1$) in the case of distance-dependent path-loss. The theoretic analysis is further provided to determine the maximum number of eavesdroppers one network can tolerate to ensure a desired performance in terms of the secrecy outage probability and transmission outage probability. The analysis results also show the proposed protocol can balance load distributed among the relays by a proper setting of r and k under the premise of specified secure and reliable requirements.

Index Terms—Two-Hop Wireless Networks, Relay Cooperation, Physical Layer Secrecy, Transmission outage, Secrecy Outage.

I. INTRODUCTION

Wireless networks have the promising applications of in many important scenarios (like battlefield networks, emergency networks, disaster recovery networks). However, Due to the energy constrained and broadcast properties, the consideration of secrecy and lifetime optimization in such networks is of great importance for ensuring the high transmission efficiency and confidentiality requirements of these applications. Two-hop wireless networks, as a building block for large multi-hop network system, have been a class of basic and important networking scenarios [1]. The analysis and design of transmission protocol in basic two-hop relay networks serves as the foundation for secure information exchange of general multi-hop network system.

For the lifetime optimization, an uneven use of the nodes may cause some nodes die much earlier, thus creating holes in the network, or worse, leaving the network disconnected, which is critical in military or emergency networks. For this

problem, a lot of protocols were proposed to balance the traffic across the various relay nodes and avoids overloading any relay node in various wireless networks, especially energy constrained wireless environments (like wireless sensor networks) [7-16](see Section V for related works). We notice there is tradeoff between the load-balance capacity and transmission efficiency and still no approaches can flexibly control it. Regarding the secrecy, the traditional cryptographic approach can provide a standard information security. However, the everlasting secrecy can not be achieved by such approach, because the adversary can record the transmitted messages and try any way to break them [12]. Especially, recent advances in high-performance computation (e.g. quantum computing) further complicate acquiring long-lasting security via cryptographic approaches [13]. This motivates the consideration of signaling scheme in physical layer secrecy framework to provide a strong form of security, where a degraded signal at an eavesdropper is always ensured such that the original data can be hardly recovered regardless of how the signal is processed at the eavesdropper [14][15][16].

The secure and reliable transmission in physical layer secrecy framework for two-hop relay wireless networks has been studied and a lot of secure transmission protocols were proposed in [17-28](see Section V for related works). These works mainly focus on the maximum secrecy capacity and minimum energy consumption, in which the system node with the best link condition to source and destination is selected as information relay. These protocols are attractive in the sense that provides very effective resistance against eavesdroppers. However, since the channel state is relatively constant during a fixed time period, some relay nodes with good link conditions always prefer to relay packages, which results in a severe load-balance problem and a quick node energy depletion. Such, these protocol is not suitable for energy-limited wireless networks (like wireless sensor networks). In order to realize load-balance, Y. Shen et al. further proposed a random relay selection protocol [29][30], in which the relay node is random selected from the system nodes. However, this protocol has lower transmission efficiency. Such, it is only suitable for large scale wireless network environment with stringent energy consumption constraint.

In summary, the available secure transmission protocols cannot provide a flexible load-balance control, which may

significantly limit their application scopes. This paper extends conventional secure cooperative transmission protocols to a general case to enable the load-balance to be flexibly controlled in the two-hop relay wireless networks without the knowledge of eavesdropper channels and locations. The main contributions of this paper are as follows:

- This paper proposes a new transmission protocol 2HR- (r, k) for two-hop relay wireless network without the knowledge eavesdropper channels and locations, where the relay is randomly selected from the first k preferable assistant relays located in the circle area with the radius r and the center at the middle between source and destination. This protocol is general protocol, and can flexibly control the tradeoff between the load-balance among relays and the transmission efficiency by a proper setting of k and r under the premise of specified secure and reliable requirements.
- In case that the path-loss is identical between all pairs of nodes, theoretic analysis of 2HR- (r, k) protocol is provided to determine the corresponding exact results on the number of eavesdroppers one network can tolerate to satisfy a specified requirement and shows that the 2HR- (r, k) protocol covers all the available secure transmission protocols as special cases, like ones with the optimal relay selection ($r = \infty, k = 1$) [19][20][27][29] and with the random relay selection ($d = \infty, k = n$ i.e. the number of system nodes)[29][30].
- In case that the path-loss between each pair of nodes also depends on the distance between them, a coordinate system is presented and the theoretic analysis of 2HR- (r, k) protocol is provided to determine the corresponding exact results on the number of eavesdroppers one network can tolerate to satisfy a specified requirement and shows that the 2HR- (r, k) protocol covers all the available secure transmission protocols as special cases, like ones with relay selected from relay selection region ($r \in (0, \infty), k = 1$)[30].

The remainder of this paper is organized as follows. Section II presents system models and the 2HR- (r, k) protocol. Section III presents the theoretic analysis in case of equal path-loss between all node pairs. Section IV presents the theoretic analysis in case that path-loss between each node pair also depends on their relative locations. Section V is related works and Section VI concludes this paper.

II. SYSTEM MODELS AND 2HR- (r, k) PROTOCOL

A. Network Model

A Two-hop wireless network scenario is considered where a source node S wishes to communicate securely with its destination node D with the help of multiple relay nodes R_1, R_2, \dots, R_n . Also present in the environment are m eavesdroppers E_1, E_2, \dots, E_m without knowledge of channels and locations. The relay nodes and eavesdroppers are independent and also uniformly distributed in the network, as illustrated in Fig.1. Our goal here is to design a general protocol to ensure the secure and reliable information transmission from source S to

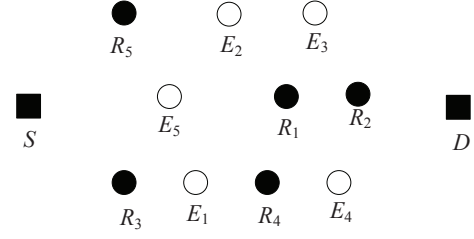


Fig. 1. System scenario: Source S wishes to communicate securely with destination D with the assistance of finite relays R_1, R_2, \dots, R_n ($n=5$ in the figure) in the presence of passive eavesdroppers E_1, E_2, \dots, E_m ($m=5$ in the figure). Cooperative relay scheme is used in the two-hop transmission.

destination D and provide flexible load-balance control among the relays.

B. Transmission Model

Consider the transmission from a transmitter A to a receiver B , and denote the i^{th} symbol transmitted by node A by $x_i^{(A)}$. We assume that all nodes transmit with the same power E_s and path-loss between all pairs of nodes is independent. We denote the frequency-nonselective multi-path fading from A to B by $h_{A,B}$. Under the condition that all nodes in a group of nodes, \mathcal{R} , are generating noises, the i^{th} signal received at node B from node A , denoted by $y_i^{(B)}$, is determined as:

$$y_i^{(B)} = \frac{h_{A,B}}{d_{A,B}^{\alpha/2}} \sqrt{E_s} x_i^{(A)} + \sum_{A_j \in \mathcal{R}} \frac{h_{A_j,B}}{d_{A_j,B}^{\alpha/2}} \sqrt{E_s} x_i^{(A_j)} + n_i^{(B)}$$

where $d_{A,B}$ is the distance between node A and B , $\alpha \geq 2$ is the path-loss exponent, $|h_{A,B}|^2$ is exponentially distributed and without loss of generality, we assume that $E[|h_{A,B}|^2] = 1$. The noise $n_i^{(B)}$ at receiver B is assumed to be i.i.d complex Gaussian random variables with mean N_0 . The SINR $C_{A,B}$ from A to B is then given by

$$C_{A,B} = \frac{E_s |h_{A,B}|^2 d_{A,B}^{-\alpha}}{\sum_{A_j \in \mathcal{R}} E_s |h_{A_j,B}|^2 d_{A_j,B}^{-\alpha} + N_0/2}$$

For a legitimate node and an eavesdropper, we use two separate SINR thresholds γ_R and γ_E to define the minimum SINR required to recover the transmitted messages for legitimate node and eavesdropper, respectively. Therefore, a system node (the selected relay or destination) is able to decode a packet if and only if its received SINR is greater than γ_R , whereas each eavesdropper try to achieve target SINR γ_E to recover the transmitted message. However, from an information-theoretic perspective, we can map to a secrecy rate formulation $R \geq \frac{1}{2} \log(1 + \gamma_R) - \frac{1}{2} \log(1 + \gamma_E)$ [31]. Hence, we can also think the γ_R and γ_E can be set by the desired secrecy rate of the system.

C. 2HR- (r, k) Protocol

Notice the available transmission protocols have their own advantages and disadvantages in terms of the transmission efficiency and energy consumption, and thus are suitable for

different network scenarios. With respect to these protocols as special cases, a general transmission protocol 2HR- (r, k) is proposed to control the balance of load distributed among the relays and works as follows.

- 1) **Relay selection region determination:** The circle area, with radius r and the center at the middle point between source S and destination D , is determined as relay selection region.
- 2) **Channel measurement:** The source S and destination D broadcast a pilot signal to allow each relay to measure the channel from S and D to itself. The relays, which receive the pilot signal, can accurately calculate $h_{S,R_j}, j = 1, 2, \dots, n$ and $h_{D,R_j}, j = 1, 2, \dots, n$.
- 3) **Candidate relay selection:** The relays with the first k large $\min(|h_{S,R_j}|^2, |h_{D,R_j}|^2)$ form the candidate relay set \mathfrak{R} . Here, R_j^r denotes the j -th relay node in the relay selection region.
- 4) **Relay selection:** The relay, indexed by j^* , is selected randomly from candidate relay set \mathfrak{R} . Using the same method with Step 2, each of the other relays $R_j, j = 1, 2, \dots, n, j \neq j^*$ in network exactly knows $h_{R_j, R_{j^*}}$.
- 5) **Two-Hop transmission:** The source S transmits the message to R_{j^*} , and concurrently, the relay nodes with indexes in $\mathcal{R}_1 = \{j \neq j^* : |h_{R_j, R_{j^*}}|^2 < \tau\}$ transmit noise to generate interference at eavesdroppers. The relay R_{j^*} then transmits the message to destination D , and concurrently, the relay nodes with indexes in $\mathcal{R}_2 = \{j \neq j^* : |h_{R_j, D}|^2 < \tau\}$ transmit noise to generate interference at eavesdroppers.

Remark 1: The load is completely balanced among the relays in the candidate relay set \mathfrak{R} whose size is determined by parameter r and k in the 2HR- (r, k) protocol. Notice that a too larger r and k may lead to larger size of the candidate relay set \mathfrak{R} . Thus, the load-balance can be flexibly controlled by a proper setting of the parameter r and k in terms of network performance requirements.

Remark 2: The parameter τ involved in the 2HR- (r, k) protocol serves as the threshold on path-loss, based on which the set of noise generating relay nodes can be identified. Notice that a too large τ may disable legitimate transmission, while a too small τ may not be sufficient for interrupting all eavesdroppers. Thus, the parameter τ should be set properly to ensure both secrecy requirement and reliability requirement.

Remark 3: In the case that there is equal path-loss between all pairs of nodes, i.e., $d_{A,B} = 1$ for all $A \neq B$, the channel state information is independent of the parameter r in 2HR- (r, k) protocol. Since the parameter r is no effect on relay selection, the relay selection region is the whole network area with $r = \infty$. Therefore, 2HR- (r, k) protocol is castrated as 2HR- (∞, k) in case of equal path-loss between all node pairs.

D. Transmission Outage and Secrecy Outage

For a Two-hop relay transmission from the source S to destination D , we call transmission outage happens if D can not receive the transmitted packet. We define the transmission outage probability, denoted by $P_{out}^{(T)}$, as the probability that transmission outage from S to D happens. For a predefined

upper bound ε_t on $P_{out}^{(T)}$, we call the communication between S and D is reliable if $P_{out}^{(T)} \leq \varepsilon_t$. Similarly, we define the transmission outage events $O_{S \rightarrow R_{j^*}}^{(T)}$ and $O_{R_{j^*} \rightarrow D}^{(T)}$ for the transmissions from S to the selected relay R_{j^*} and from R_{j^*} to D , respectively. Due to the link independence assumption, we have

$$P_{out}^{(T)} = P\left(O_{S \rightarrow R_{j^*}}^{(T)}\right) + P\left(O_{R_{j^*} \rightarrow D}^{(T)}\right) - P\left(O_{S \rightarrow R_{j^*}}^{(T)}\right) \cdot P\left(O_{R_{j^*} \rightarrow D}^{(T)}\right) \quad (1)$$

Regarding the secrecy outage, we call secrecy outage happens for a transmission from S to D if at least one eavesdropper can recover the transmitted packets during the process of this two-hop transmission. We define the secrecy outage probability, denoted by $P_{out}^{(S)}$, as the probability that secrecy outage happens during the transmission from S to D . For a predefined upper bound ε_s on $P_{out}^{(S)}$, we call the communication between S and D is secure if $P_{out}^{(S)} \leq \varepsilon_s$. Similarly, we define the secrecy outage events $O_{S \rightarrow R_{j^*}}^{(S)}$ and $O_{R_{j^*} \rightarrow D}^{(S)}$ for the transmissions from S to the selected relay R_{j^*} and from R_{j^*} to D , respectively. Due to the link independence assumption, we have

$$P_{out}^{(S)} = P\left(O_{S \rightarrow R_{j^*}}^{(S)}\right) + P\left(O_{R_{j^*} \rightarrow D}^{(S)}\right) - P\left(O_{S \rightarrow R_{j^*}}^{(S)}\right) \cdot P\left(O_{R_{j^*} \rightarrow D}^{(S)}\right) \quad (2)$$

III. EQUAL PATH-LOSS BETWEEN ALL NODE PAIRS

In this section, we analyze 2HR- (r, k) protocol in the case where the path-loss is equal between all pairs of nodes in the system. The Remark 3 shows 2HR- (r, k) protocol is castrated as 2HR- (∞, k) in case of equal path-loss between all node pairs. We now analyze that under the 2HR- (∞, k) protocol the number of eavesdroppers one network can tolerate subject to specified requirements on transmission outage and secrecy outage. The following two lemmas regarding some basic properties of $P_{out}^{(T)}$, $P_{out}^{(S)}$ and τ are first presented, which will help us to derive the main result in Theorem 1.

Lemma 1: Consider the network scenario of Fig 1 with equal path-loss between all pairs of nodes, under the 2HR- (r, k) protocol the transmission outage probability $P_{out}^{(T)}$ and secrecy outage probability $P_{out}^{(S)}$ there satisfy the following conditions.

$$P_{out}^{(T)} \leq 2 \left(\frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1 - \Psi]^i \Psi^{n-i} \right] \right)^2 \quad (3)$$

$$- \left(\frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1 - \Psi]^i \Psi^{n-i} \right] \right)^2$$

here $\Psi = e^{-2\gamma_R(n-1)(1-e^{-\tau})\tau}$, and

$$P_{out}^{(S)} \leq 2m \cdot \left(\frac{1}{1+\gamma_E} \right)^{(n-1)(1-e^{-\tau})} - \left[m \cdot \left(\frac{1}{1+\gamma_E} \right)^{(n-1)(1-e^{-\tau})} \right]^2 \quad (4)$$

The proof of Lemma 1 can be found in the Appendix A.

Lemma 2: Consider the network scenario of Fig 1 with equal path-loss between all pairs of nodes, to ensure $P_{out}^{(T)} \leq \varepsilon_t$ and $P_{out}^{(S)} \leq \varepsilon_s$ under the 2HR-(r, k) protocol, the parameter τ must satisfy the following condition.

$$\tau \leq \sqrt{\frac{-\log \left(\left[\left(\left\lfloor \frac{k}{2} \right\rfloor \right) (1 + k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1 \right)}{2\gamma_R(n-1)}}$$

and

$$\tau \geq -\log \left[1 + \frac{\log \left(\frac{1-\sqrt{1-\varepsilon_s}}{m} \right)}{(n-1)\log(1+\gamma_E)} \right]$$

here, $\lfloor \cdot \rfloor$ is the floor function.

Proof:

The parameter τ should be set properly to satisfy both reliability and secrecy requirements.

• Reliability Guarantee

To ensure the reliability requirement $P_{out}^{(T)} \leq \varepsilon_t$, we know from formula (3) in the Lemma 1, that we just need

$$2 \left(\frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1-\Psi]^i \Psi^{n-i} \right] \right) - \left(\frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1-\Psi]^i \Psi^{n-i} \right] \right)^2 \leq \varepsilon_t$$

Thus,

$$\frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1-\Psi]^i \Psi^{n-i} \right] \leq 1 - \sqrt{1-\varepsilon_t} \quad (5)$$

Notice that

$$\begin{aligned} & \frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} (1-\Psi)^i \Psi^{n-i} \right] \\ &= \frac{1}{k} \sum_{j=1}^k \left[1 - \sum_{i=0}^{n-j} \binom{n}{i} (1-\Psi)^i \Psi^{n-i} \right] \\ &= \frac{1}{k} \sum_{j=1}^k \left[1 - \sum_{i=0}^{n-j} \frac{\binom{n}{i}}{\binom{n-j}{i}} \binom{n-j}{i} (1-\Psi)^i \Psi^{n-j-i} \Psi^j \right] \end{aligned} \quad (6)$$

We also notice the i can take from 0 to $n-j$, then we have

$$1 \leq \frac{\binom{n}{i}}{\binom{n-j}{i}} \leq \frac{n!}{(n-j)!j!}$$

Substituting into formula (6), we have

$$\begin{aligned} & \frac{1}{k} \sum_{j=1}^k \left[1 - \sum_{i=0}^{n-j} \frac{\binom{n}{i}}{\binom{n-j}{i}} \binom{n-j}{i} (1-\Psi)^i \Psi^{n-j-i} \Psi^j \right] \\ & \leq \frac{1}{k} \sum_{j=1}^k \left[1 - \Psi^j \cdot \sum_{i=0}^{n-j} \binom{n-j}{i} (1-\Psi)^i \Psi^{n-j-i} \right] \\ &= 1 - \frac{1}{k} \sum_{j=1}^k \Psi^j \\ &= 1 - \frac{1}{k} \left[\sum_{j=0}^k \frac{1}{\binom{k}{j}} \binom{k}{j} \Psi^j - 1 \right] \\ & \leq 1 - \frac{1}{k} \left[\frac{1}{\left(\left\lfloor \frac{k}{2} \right\rfloor \right)} \sum_{j=0}^k \binom{k}{j} \Psi^j - 1 \right] \\ &= 1 - \frac{1}{k} \left[\frac{1}{\left(\left\lfloor \frac{k}{2} \right\rfloor \right)} (1+\Psi)^k - 1 \right] \end{aligned} \quad (7)$$

According to formula (5), (6) and (7), in order to ensure the reliability, we need

$$1 - \frac{1}{k} \left[\frac{1}{\left(\left\lfloor \frac{k}{2} \right\rfloor \right)} (1+\Psi)^k - 1 \right] \leq 1 - \sqrt{1-\varepsilon_t}$$

or equally,

$$\Psi \geq \left[\left(\left\lfloor \frac{k}{2} \right\rfloor \right) (1 + k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1$$

that is,

$$e^{-2\gamma_R(n-1)(1-e^{-\tau})\tau} \geq \left[\left(\left\lfloor \frac{k}{2} \right\rfloor \right) (1 + k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1$$

Therefore

$$(1-e^{-\tau})\tau \leq \frac{-\log \left(\left[\left(\left\lfloor \frac{k}{2} \right\rfloor \right) (1 + k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1 \right)}{2\gamma_R(n-1)}$$

By using Taylor formula, we have

$$\tau \leq \sqrt{\frac{-\log \left(\left[\left(\left\lfloor \frac{k}{2} \right\rfloor \right) (1 + k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1 \right)}{2\gamma_R(n-1)}}$$

• Secrecy Guarantee

To ensure the secrecy requirement $P_{out}^{(S)} \leq \varepsilon_s$, we know from Lemma 1 that we just need

$$\begin{aligned}
& 2m \cdot \left(\frac{1}{1+\gamma_E} \right)^{(n-1)(1-e^{-\tau})} \\
& - \left[m \cdot \left(\frac{1}{1+\gamma_E} \right)^{(n-1)(1-e^{-\tau})} \right]^2 \\
& \leq \varepsilon_s
\end{aligned}$$

Thus,

$$m \cdot \left(\frac{1}{1+\gamma_E} \right)^{(n-1)(1-e^{-\tau})} \leq 1 - \sqrt{1-\varepsilon_s}$$

That is,

$$\tau \geq -\log \left[1 + \frac{\log \left(\frac{1-\sqrt{1-\varepsilon_s}}{m} \right)}{(n-1) \log(1+\gamma_E)} \right]$$

Based on the results of Lemma 2, we now can establish the following theorem regarding the performance of the proposed protocol in case of equal path-loss between all node pairs.

Theorem 1. Consider the network scenario of Fig 1 with equal path-loss between all pairs of nodes. To guarantee $P_{out}^{(T)} \leq \varepsilon_t$ and $P_{out}^{(S)} \leq \varepsilon_s$ under 2HR- (r, k) protocol, the number of eavesdroppers m the network can tolerate must satisfy the following condition.

$$m \leq \frac{1 - \sqrt{1-\varepsilon_s}}{\left(\frac{1}{1+\gamma_E} \right) \sqrt{\frac{-(n-1) \log \left(\left[\left(\lfloor \frac{k}{2} \rfloor \right) (1+k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1 \right)}{2\gamma_R}}}$$

Proof:

From Lemma 2, we know that to ensure the reliability requirement, we have

$$\tau \leq \sqrt{\frac{-\log \left(\left[\left(\lfloor \frac{k}{2} \rfloor \right) (1+k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1 \right)}{2\gamma_R(n-1)}} \quad (8)$$

and

$$(n-1)(1-e^{-\tau}) \leq \frac{-\log \left(\left[\left(\lfloor \frac{k}{2} \rfloor \right) (1+k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1 \right)}{2\gamma_R\tau} \quad (9)$$

To ensure the secrecy requirement, we need

$$\left(\frac{1}{1+\gamma_E} \right)^{(n-1)(1-e^{-\tau})} \leq \frac{1 - \sqrt{1-\varepsilon_s}}{m} \quad (10)$$

From formula (9) and (10), we can get

$$\begin{aligned}
m & \leq \frac{1 - \sqrt{1-\varepsilon_s}}{\left(\frac{1}{1+\gamma_E} \right)^{(n-1)(1-e^{-\tau})}} \\
& \leq \frac{1 - \sqrt{1-\varepsilon_s}}{\left(\frac{1}{1+\gamma_E} \right)^{\frac{-\log \left(\left[\left(\lfloor \frac{k}{2} \rfloor \right) (1+k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1 \right)}{2\gamma_R\tau}}}
\end{aligned} \quad (11)$$

By letting τ take its maximum value for maximum interference at eavesdroppers, from formula (8) and (11), we get the following bound

$$m \leq \frac{1 - \sqrt{1-\varepsilon_s}}{\left(\frac{1}{1+\gamma_E} \right) \sqrt{\frac{-(n-1) \log \left(\left[\left(\lfloor \frac{k}{2} \rfloor \right) (1+k\sqrt{1-\varepsilon_t}) \right]^{\frac{1}{k}} - 1 \right)}{2\gamma_R}}}$$

Based on the above analysis, by simple derivation, we can get the follow corollary to show our proposal is a general protocol.

Corollary 1. Consider the network scenario of Fig 1 with equal path-loss between all pairs of nodes, the analysis results of the proposed protocol is identical to that of protocols with the optimal relay selection presented in [19][20] by setting of $k = 1$ and $r = \infty$, and is identical to that of protocols with the random relay selection presented in [29][30] by setting of $k = n$ and $r = \infty$.

Remark 4: In case of equal path-loss of all pairs of nodes and the parameter $r = \infty$, we notice that the larger k means the better load-balance among the relays and the lower transmission efficiency, and vice versa. In particular, when $k = 1$, 2HR- (r, k) protocol has the worse load-balance among the relays and the highest transmission efficiency, and when $k = n$, 2HR- (r, k) protocol has the best load-balance among the relays and the lower transmission efficiency.

IV. GENERAL CASE TO ADDRESSING PATH-LOSS

In this section, we consider the more general scenario where the path-loss between each pair of nodes also depends on the distance between them. The related theoretic analysis is further provided to determine the number of eavesdroppers one network can tolerant by adopting the 2HR- (r, k) protocol. To address the distance-dependent path-loss, we consider a coordination system shown in Fig 2, in which the two-hop relay wireless networks employed in the 2-D plane of unit area, consisting of the square $[-0.5, 0.5] \times [-0.5, 0.5]$. The source S located at coordinate $(-0.5, 0)$ wishes to establish two-hop transmission with destination D located at coordinate $(0.5, 0)$.

To address the near eavesdropper problem and also to simply the analysis for the 2HR- (r, k) protocol, we assume that there exists a constant $d_0 > 0$ such that any eavesdropper falling within a circle area with radius d_0 and center S or R_{j^*} can eavesdrop the transmitted messages successfully with

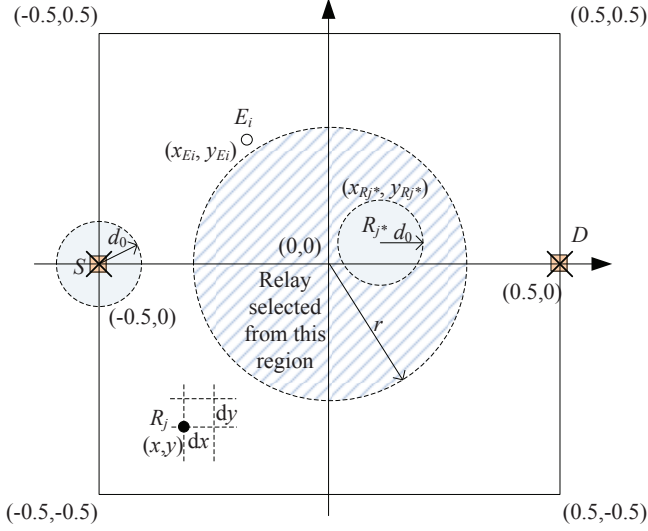


Fig. 2. Coordinate system for the scenario where path-loss between pairs of nodes is based on their relative locations.

probability 1, while any eavesdropper beyond such area can only successfully eavesdrop the transmitted messages with a probability less than 1. Based on such a simplification, we can establish the following two lemmas regarding some basic properties of $P_{out}^{(T)}$, $P_{out}^{(S)}$ and τ under this protocol.

Lemma 3: Consider the network scenario of Fig 2, under the 2HR- (r, k) protocol the transmission outage probability $P_{out}^{(T)}$ and secrecy outage probability $P_{out}^{(S)}$ there satisfy the following condition.

$$P_{out}^{(T)} \leq 1 - \Upsilon^{\varphi_1 + \varphi_2} \sum_{l=1}^k \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} - \frac{\Upsilon^{2(\varphi_1 + \varphi_2)}}{k^2} \sum_{l=k+1}^n \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} \quad (12)$$

$$P_{out}^{(S)} \leq 2m \left[\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \right] - \left[m \left(\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \right) \right]^2 \quad (13)$$

here,

$$\Upsilon = e^{-\frac{\gamma_R \tau (n-1) (1-e^{-\tau})}{(0.5+r)^\alpha}}$$

$$\varphi_1 = \int_{-0.5}^{0.5} \int_{-0.5}^{0.5} \frac{1}{(x^2 + y^2)^{\frac{\alpha}{2}}} dx dy$$

$$\varphi_2 = \int_{-0.5}^{0.5} \int_{-0.5}^{0.5} \frac{1}{[(x-0.5)^2 + y^2]^{\frac{\alpha}{2}}} dx dy$$

$$\psi = \int_{-0.5}^{0.5} \int_{-0.5}^{0.5} \frac{1}{[(x-0.5)^2 + (y-0.5)^2]^{\frac{\alpha}{2}}} dx dy$$

The proof of Lemma 3 can be found in the Appendix B.
Lemma 4: Consider the network scenario of Fig 2, to ensure $P_{out}^{(T)} \leq \varepsilon_t$ and $P_{out}^{(S)} \leq \varepsilon_s$ by applying 2HR- (r, k) protocol, the parameter τ must satisfy the following condition.

$$\tau \leq \sqrt{\frac{-\log \left[\frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_t)\nu_2} - k^2 \nu_1}{2\nu_2} \right]}{\gamma_R (n-1) (\varphi_1 + \varphi_2) (0.5+r)^\alpha}}$$

and

$$\tau \geq -\log \left[1 + \frac{\log \left(\frac{\frac{1-\sqrt{1-\varepsilon_s}}{m} - \pi d_0^2}{1 - \pi d_0^2} \right)}{(n-1) \log(1 + \gamma_E \psi d_0^\alpha)} \right]$$

here, φ_1 , φ_2 , and ψ are defined in the same way as that in Lemma 3, and

$$\nu_1 = k^2 \sum_{l=1}^k \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l}$$

$$\nu_2 = k^2 \sum_{l=k+1}^n \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l}$$

Proof:

The parameter τ should be set properly to satisfy both reliability and secrecy requirements.

• **Reliability Guarantee**

To ensure the reliability requirement $P_{out}^{(T)} \leq \varepsilon_t$, we know from formula (12) in Lemma 3 that we just need

$$1 - \Upsilon^{\varphi_1 + \varphi_2} \sum_{l=1}^k \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} - \frac{\Upsilon^{2(\varphi_1 + \varphi_2)}}{k^2} \sum_{l=k+1}^n \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} \leq \varepsilon_t$$

Thus,

$$\Upsilon^{\varphi_1 + \varphi_2} \geq \frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_t)\nu_2} - k^2 \nu_1}{2\nu_2}$$

here

$$\nu_1 = k^2 \sum_{l=1}^k \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l}$$

$$\nu_2 = k^2 \sum_{l=k+1}^n \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l}$$

That is,

$$e^{-\frac{\gamma_R \tau (n-1) (1-e^{-\tau}) (\varphi_1 + \varphi_2)}{(0.5+r)^{-\alpha}}} \geq \frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_t)\nu_2} - k^2 \nu_1}{2\nu_2}$$

Thus,

$$\tau (1 - e^{-\tau}) \leq \frac{-\log \left[\frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_t)\nu_2} - k^2 \nu_1}{2\nu_2} \right]}{\gamma_R (n-1) (\varphi_1 + \varphi_2) (0.5+r)^\alpha}$$

By using Taylor formula, we have

$$\tau \leq \sqrt{\frac{-\log \left[\frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_t)\nu_2} - k^2 \nu_1}{2\nu_2} \right]}{\gamma_R (n-1) (\varphi_1 + \varphi_2) (0.5+r)^\alpha}}$$

• Secrecy Guarantee

To ensure the secrecy requirement $P_{out}^{(S)} \leq \varepsilon_s$, we know from formula (13) in Lemma 3 that we just need

$$2m \left[\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \right] - \left[m \left(\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \right) \right]^2 \leq \varepsilon_s$$

Thus,

$$m \cdot \left[\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \right] \leq 1 - \sqrt{1 - \varepsilon_s}$$

that is,

$$\tau \geq -\log \left[1 + \frac{\log \left(\frac{1 - \sqrt{1 - \varepsilon_s} - \pi d_0^2}{1 - \pi d_0^2} \right)}{(n-1) \log (1 + \gamma_E \psi d_0^\alpha)} \right]$$

Based on the results of Lemma 4, we now can establish the following theorem regarding the performance of 2HR-(r, k) protocol.

Theorem 2. Consider the network scenario of Fig 2. To guarantee $P_{out}^{(T)} \leq \varepsilon_t$ and $P_{out}^{(S)} \leq \varepsilon_s$ based on the proposed 2HR-(r, k) protocol, the number of eavesdroppers m the network can tolerate must satisfy the following condition.

$$m \leq \frac{1 - \sqrt{1 - \varepsilon_s}}{\pi d_0^2 + (1 - \pi d_0^2) \omega}$$

here

$$\omega = \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right) \sqrt{\frac{-(n-1) \log \left[\frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_t)\nu_2} - k^2 \nu_1}{2\nu_2} \right]}{\gamma_R (\varphi_1 + \varphi_2) (0.5+r)^\alpha}}$$

$\varphi_1, \varphi_2, \nu_1, \nu_2$ and ψ are defined in the same way as that in Lemma 3 and Lemma 4.

Proof:

From Lemma 4, we know that to ensure the reliability requirement, we have

$$\tau \leq \sqrt{\frac{-\log \left[\frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_t)\nu_2} - k^2 \nu_1}{2\nu_2} \right]}{\gamma_R (n-1) (\varphi_1 + \varphi_2) (0.5+r)^\alpha}} \quad (14)$$

and

$$(n-1) (1 - e^{-\tau}) \leq \frac{-\log \left[\frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_t)\nu_2} - k^2 \nu_1}{2\nu_2} \right]}{\gamma_R \tau (\varphi_1 + \varphi_2) (0.5+r)^\alpha} \quad (15)$$

To ensure the secrecy requirement, we need

$$m \cdot \left[\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \right] \leq 1 - \sqrt{1 - \varepsilon_s} \quad (16)$$

From formula (15) and (16), we can get

$$m \leq \frac{1 - \sqrt{1 - \varepsilon_s}}{\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2)} \leq \frac{1 - \sqrt{1 - \varepsilon_s}}{\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{\frac{-\log \left[\frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_t)\nu_2} - k^2 \nu_1}{2\nu_2} \right]}{\gamma_R (\varphi_1 + \varphi_2) (0.5+r)^\alpha}} (1 - \pi d_0^2)} \quad (17)$$

By letting τ take its maximum value for maximum interference at eavesdroppers, from formula (14) and (17), we get the following bound

$$m \leq \frac{1 - \sqrt{1 - \varepsilon_s}}{\pi d_0^2 + (1 - \pi d_0^2) \omega}$$

here

$$\omega = \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right) \sqrt[\frac{-(n-1) \log \left[\frac{k^2 \sqrt{\nu_1^2 + 4(1-\varepsilon_f)\nu_2} - k^2 \nu_1}{2\nu_2} \right]}{\gamma_R (\varphi_1 + \varphi_2) (0.5+r)^\alpha}]{}$$

Remark 5: The parameter r determines the relay selection region. When parameter r tends to 0, few system nodes locate in relay selection region, and the relay selection process tends to optimal from the view of relay selection region with less load-balance capacity. With increasing of parameter r , the more relays are in relay selection region, which can ensure better load-balance.

Remark 6: The SINR at the receiver depends on channel state information and the distance between the transmitter and receiver. The *Remark 4* and *Remark 5* show that the parameter r and k in 2HR- (r, k) protocol can be flexibly set to control the tradeoff the load-balance and the transmission efficiency in terms of channel state information and the distance between the transmitter and receiver respectively.

Remark 7: In order to get the better load-balance, set a larger r and k which will result in a lower transmission efficiency. The Theorem 1 and Theorem 3 show that the number of eavesdroppers one network can tolerant is decreasing as the increasing r and k .

Remark 8: In the initial stage of the network operation, the parameter r and k can be set small values to ensure the high efficiency, since all relays are energetic which load-balance among the relays is not first considered. With the passage of time of the network operation, the parameter r and k can be gradually set higher values for better load-balance among the relays to extend the network lifetime.

Based on the above analysis, by simple derivation, we can get the follow corollary to show our proposal is a general protocol.

Corollary 2. Consider the network scenario of Fig 2, the analysis results of the proposed protocol with $r \rightarrow \infty$ and $k = n$ is identical to that of Protocol 3 with $a = 0$ and $b = 0$ (the parameters a and b determine the relay selection region) proposed in [30], and the analysis results of the proposed protocol with $r \rightarrow 0$ and $k = n$ is identical to that of Protocol 3 with $a \rightarrow 0.5$ and $b \rightarrow 0.5$ proposed in [30].

Remark 9: The protocol proposed in [30] have the ability to control load-balance among the relays by only control on the relay selection region. Whereas, 2HR- (r, k) protocol can realize load-balance by control on both relay selection set and relay selection region.

V. RELATED WORKS

A lot of research works have been dedicated to load-balance transmission scheme for balanced energy consumption among system nodes to prolong the network lifetime in wireless networks. A few dynamic load balancing strategies and schemes were proposed in [2][3] for distributed systems. For wireless mesh network, a multi-hop transmission scheme is proposed in [4], in which information relay is selected based on the current load of the relay nodes. For wireless access networks,

a distributed routing algorithm that performs dynamic load-balance by constructs a load-balanced backbone tree [5]. J. Gao et al. extended the shortest path routing to support load-balance [6]. In particular, for energy constrained wireless sensor networks, load-balance is significant important, and a lot of transmission schemes were proposed for load-balance among relays and prolonging the network lifetime [7][8][9]. Lifetime optimization and security of multi-hop wireless networks was further considered and the secure transmission scheme with load-balance is proposed in [10][11].

Recently, attention is turning to achieve physical layer secrecy and secure transmission scheme via cooperative relays is considered in large wireless networks. Some transmission protocols are proposed to select the optimal relay in terms of the maximum secrecy capacity or minimum transmit power. In case that eavesdropper channels or locations is known, node cooperation is used to improve the performance of secure wireless communications and a few cooperative transmission protocols were proposed to jam eavesdroppers [17][18]. In case that eavesdropper channels or locations is unknown, D. Goeckel et al. proposed a transmission protocol based on optimal relay selection [19][20]. For both one-dimensional and two-dimensional networks, a secure transmission protocol is proposed in [21]. Z. Ding et al. considered the opportunistic use of relays and proposed two secrecy transmission protocols [22]. The "two-way secrecy scheme" was studied in [23][24] and M. Dehghan et al. explored the energy efficiency of cooperative jamming scheme [25]. A. Sheikholeslami et al. proposed a protocol, where the signal of a given transmitter is protected by the aggregate interference produced by the other transmitters [26]. A secure transmission protocol are presented in case where the eavesdroppers collude [27]. J. Li et al. proposed two secure transmission protocols to confound the eavesdroppers [28]. The above works mainly focus on the maximum the secrecy capacity, in which the system nodes with best link condition is always selected as information relay. Such, these protocols have less load-balance capacity. In order to address this problem, Y. Shen et al. further proposed a protocol with random relay selection in [29][30]. This protocol can provide good load-balance capacity and balanced energy consumption among the relays, whereas it has low transmission efficiency.

VI. CONCLUSION

This paper proposed a general 2HR- (r, k) protocol to ensure secure and reliable information transmission through multiple cooperative system nodes for two-hop relay wireless networks without the knowledge of eavesdropper channels and locations. We proved that the 2HR- (r, k) protocol has the capability of flexible control over the tradeoff between the load-balance capacity and the transmission efficiency by a proper setting of the radius r of relay selection region and the size k of candidate relay set. Such, in general it is possible for us to set proper value of parameters according to network scenario to support various applications. The results in this paper indicate that the parameters r and k of the 2HR- (r, k) protocol do also affect the number of eavesdroppers one networks can

tolerant under the premise of specified secure and reliable requirements.

APPENDIX A PROOF OF LEMMA 1

Proof:

Based on the definition of transmission outage probability, we have

$$\begin{aligned}
 P\left(O_{S \rightarrow R_{j^*}}^{(T)}\right) &= P\left(C_{S, R_{j^*}} \leq \gamma_R\right) \\
 &= P\left(\frac{E_s \cdot |h_{S, R_{j^*}}|^2}{\sum_{R_j \in \mathcal{R}_1} E_s \cdot |h_{R_j, R_{j^*}}|^2 + N_0/2} \leq \gamma_R\right) \\
 &\doteq P\left(\frac{|h_{S, R_{j^*}}|^2}{\sum_{R_j \in \mathcal{R}_1} |h_{R_j, R_{j^*}}|^2} \leq \gamma_R\right) \\
 &\leq P\left(\frac{H}{|\mathcal{R}_1|^\tau} \leq \gamma_R\right) \\
 &= P(H \leq \gamma_R |\mathcal{R}_1|^\tau)
 \end{aligned}$$

Here, $H = \min(|h_{S, R_{j^*}}|^2, |h_{D, R_{j^*}}|^2)$. Compared to the noise generated by multiple system nodes, the environment noise is negligible and thus is omitted here to simply the analysis. Notice that $\mathcal{R}_1 = \{j \neq j^* : |h_{R_j, R_{j^*}}|^2 < \tau\}$.

Employing Appendix C, we should have

$$\begin{aligned}
 P\left(O_{S \rightarrow R_{j^*}}^{(T)}\right) &\leq F_H(\gamma_R |\mathcal{R}_1|^\tau) \\
 &= \frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} \right. \\
 &\quad \left. \left[1 - e^{-2\gamma_R |\mathcal{R}_1|^\tau}\right]^i \left[e^{-2\gamma_R |\mathcal{R}_1|^\tau}\right]^{n-i} \right]
 \end{aligned}$$

Since there are $n-1$ other relays except R_{j^*} , the expected number of noise-generation nodes is given by $|\mathcal{R}_1| = (n-1) \cdot P(|h_{R_j, R_{j^*}}|^2 < \tau) = (n-1)(1 - e^{-\tau})$. Then we have

$$\begin{aligned}
 P\left(O_{S \rightarrow R_{j^*}}^{(T)}\right) &\leq \frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} \right. \\
 &\quad \left. \left[1 - e^{-2\gamma_R (n-1)(1-e^{-\tau})}\right]^i \left[e^{-2\gamma_R (n-1)(1-e^{-\tau})}\right]^{n-i} \right]
 \end{aligned}$$

For convenience of the description, let $\Psi = e^{-2\gamma_R (n-1)(1-e^{-\tau})}$, and we have

$$P\left(O_{S \rightarrow R_{j^*}}^{(T)}\right) \leq \frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1 - \Psi]^i \Psi^{n-i} \right] \quad (18)$$

Employing the same method, we can get

$$P\left(O_{R_{j^*} \rightarrow D}^{(T)}\right) \leq \frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1 - \Psi]^i \Psi^{n-i} \right] \quad (19)$$

Substituting formula (18) and (19) into formula (1), we have

$$\begin{aligned}
 P_{out}^{(T)} &\leq 2 \left(\frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1 - \Psi]^i \Psi^{n-i} \right] \right) \\
 &\quad - \left(\frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1 - \Psi]^i \Psi^{n-i} \right] \right)^2
 \end{aligned}$$

According to the definition of secrecy outage probability, we know that

$$P\left(O_{S \rightarrow R_{j^*}}^{(S)}\right) = P\left(\bigcup_{i=1}^m \{C_{S, E_i} \geq \gamma_E\}\right)$$

Thus, we have

$$P\left(O_{S \rightarrow R_{j^*}}^{(S)}\right) \leq \sum_{i=1}^m P(C_{S, E_i} \geq \gamma_E) \quad (20)$$

Based on the Markov inequality,

$$\begin{aligned}
 P(C_{S, E_i} \geq \gamma_E) &\leq P\left(\frac{E_s \cdot |h_{S, E_i}|^2}{\sum_{R_j \in \mathcal{R}_1} E_s \cdot |h_{R_j, E_i}|^2} \geq \gamma_E\right) \\
 &= E_{\{h_{R_j, E_i}, j=0, 1, \dots, n+mp, j \neq j^*\}, \mathcal{R}_1} \left[P\left(|h_{S, E_i}|^2 > \gamma_E \cdot \sum_{R_j \in \mathcal{R}_1} |h_{R_j, E_i}|^2\right) \right] \\
 &\leq E_{\mathcal{R}_1} \left[\prod_{R_j \in \mathcal{R}_1} E_{h_{R_j, E_i}} \left[e^{-\gamma_E |h_{R_j, E_i}|^2} \right] \right] \\
 &= E_{\mathcal{R}_1} \left[\left(\frac{1}{1 + \gamma_E} \right)^{|\mathcal{R}_1|} \right]
 \end{aligned}$$

Substituting into formula (20), we have

$$P\left(O_{S \rightarrow R_{j^*}}^{(S)}\right) \leq \sum_{i=1}^m \left(\frac{1}{1 + \gamma_E} \right)^{|\mathcal{R}_1|} = m \cdot \left(\frac{1}{1 + \gamma_E} \right)^{|\mathcal{R}_1|} \quad (21)$$

employing the same method, we can get

$$P\left(O_{R_{j^*} \rightarrow D}^{(S)}\right) \leq m \cdot \left(\frac{1}{1 + \gamma_E} \right)^{|\mathcal{R}_2|} \quad (22)$$

Since the expected number of noise-generation nodes is given by $|\mathcal{R}_1| = |\mathcal{R}_2| = (n-1)(1 - e^{-\tau})$, thus, substituting formula (21) and (22) into formula (2), we can get

$$P_{out}^{(S)} \leq 2m \cdot \left(\frac{1}{1 + \gamma_E} \right)^{(n-1)(1-e^{-\tau})} - \left[m \cdot \left(\frac{1}{1 + \gamma_E} \right)^{(n-1)(1-e^{-\tau})} \right]^2$$

■

APPENDIX B PROOF OF LEMMA 3

Proof:

Notice that two ways leading to transmission outage are: 1) there are no candidate relays in the relay selection region; 2) the SINR at the selected relay or the destination is less than γ_R . We also notice that if the number of the eligible relays in candidate relay region less than or equal to k , the relay will be random selected from candidate relay set \mathfrak{R} .

Let A_l , $l = 0, 1, \dots, n$, be the event that there are just l system nodes in the relay selection region. We have

$$P_{out}^{(T)} = \sum_{l=0}^n P_{out|A_l}^{(T)} \cdot P(A_l) \quad (23)$$

Since the relay is uniformly distributed, the number of relays in candidate relay region is a binomial distribution $(n, \pi r^2)$. We have

$$P(A_l) = \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} \quad (24)$$

$P_{out|A_l}^{(T)}$ is discussed from the following three aspects.

1) $l = 0$

In this case, there are no relays in the relay selection region, then, we have

$$P_{out|A_l}^{(T)} = 1 \quad (25)$$

2) $1 \leq l \leq k$

Since the number of candidate relay nodes is less than or equal to k . The relay selection process is to select relay randomly in the candidate relay set \mathfrak{R} which consists of these l relays located in the relay selection region.

Notice $P_{out|A_l}^{(T)}$ is determined as

$$P_{out|A_l}^{(T)} = P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) + P\left(O_{R_{j^*} \rightarrow D}^{(T)} \middle| A_l\right) - P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) \cdot P\left(O_{R_{j^*} \rightarrow D}^{(T)} \middle| A_l\right) \quad (26)$$

Based on the definition of transmission outage probability, we have

$$\begin{aligned} P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) &= P\left(C_{S, R_{j^*}} \leq \gamma_R \middle| A_l\right) \\ &= P\left(\frac{E_s \cdot \frac{|h_{S, R_{j^*}}|^2}{d_{S, R_{j^*}}^\alpha}}{\sum_{R_j \in \mathcal{R}_1} E_s \cdot \frac{|h_{R_j, R_{j^*}}|^2}{d_{R_j, R_{j^*}}^\alpha} + \frac{N_0}{2}} \leq \gamma_R \middle| A_l\right) \\ &\doteq P\left(\frac{\frac{|h_{S, R_{j^*}}|^2}{d_{S, R_{j^*}}^\alpha}}{\sum_{R_j \in \mathcal{R}_1} \frac{|h_{R_j, R_{j^*}}|^2}{d_{R_j, R_{j^*}}^\alpha}} \leq \gamma_R \middle| A_l\right) \end{aligned}$$

Compared to the noise generated by multiple system nodes, the environment noise is negligible and thus is omitted here to simply the analysis. Notice that $\mathcal{R}_1 = \{j \neq j^* : |h_{R_j, R_{j^*}}|^2 < \tau\}$, then

$$P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) \leq P\left(\frac{|h_{S, R_{j^*}}|^2 d_{S, R_{j^*}}^{-\alpha}}{\sum_{R_j \in \mathcal{R}_1} \tau d_{R_j, R_{j^*}}^{-\alpha}} \leq \gamma_R \middle| A_l\right)$$

Without loss of generality, Let (x, y) be the coordinate of R_j , shown in Fig 2. The number of noise generation nodes in square $[x, x + dx] \times [y, y + dy]$ is $(n-1)(1-e^{-\tau}) dx dy$. Then, we have

$$\begin{aligned} \sum_{R_j \in \mathcal{R}_1} \frac{\tau}{d_{R_j, R_{j^*}}^\alpha} &= \int_0^1 \int_0^1 \frac{\tau (n-1) (1-e^{-\tau})}{\left[(x-x_{R_{j^*}})^2 + (y-y_{R_{j^*}})^2\right]^{\frac{\alpha}{2}}} dx dy \end{aligned}$$

where $(x_{R_{j^*}}, y_{R_{j^*}})$ is the coordinate of the selected relay R_{j^*} which locates in the relay selection region. Because the relays are uniformly distributed, it is the worst case that the selected relay R_{j^*} is located on the point $(0, 0)$, where the interference at R_{j^*} from the noise generation nodes is largest, and the best case with the selected relay R_{j^*} located in the edge of the circular relay selection region, where the interference at R_{j^*} from the noise generation nodes is lowest. Then, we consider the worst case and have

$$P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) \leq P\left(\frac{|h_{S, R_{j^*}}|^2 d_{S, R_{j^*}}^{-\alpha}}{\tau (n-1) (1-e^{-\tau}) \varphi_1} \leq \gamma_R \middle| A_l\right)$$

here,

$$\varphi_1 = \int_{-0.5}^{0.5} \int_{-0.5}^{0.5} \frac{1}{(x^2 + y^2)^{\frac{\alpha}{2}}} dx dy$$

Due to $0.5 - r \leq d_{S, R_{j^*}} \leq 0.5 + r$, then,

$$\begin{aligned}
& P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) \\
& \leq P\left(\frac{|h_{S,R_{j^*}}|^2 (0.5+r)^{-\alpha}}{\tau(n-1)(1-e^{-\tau})\varphi_1} \leq \gamma_R \middle| A_l\right) \\
& = P\left(|h_{S,R_{j^*}}|^2 \leq \frac{\gamma_R \tau (n-1)(1-e^{-\tau})\varphi_1}{(0.5+r)^{-\alpha}} \middle| A_l\right) \\
& = 1 - e^{-\frac{\gamma_R \tau (n-1)(1-e^{-\tau})\varphi_1}{(0.5+r)^{-\alpha}}}
\end{aligned}$$

For convenience of description, let $\Upsilon = e^{-\frac{\gamma_R \tau (n-1)(1-e^{-\tau})\varphi_1}{(0.5+r)^{-\alpha}}}$, we have

$$P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) \leq 1 - \Upsilon^{\varphi_1} \quad (27)$$

Employing the same method, we can get

$$P\left(O_{R_{j^*} \rightarrow D}^{(T)} \middle| A_l\right) \leq 1 - \Upsilon^{\varphi_2} \quad (28)$$

here,

$$\varphi_2 = \int_{-0.5}^{0.5} \int_{-0.5}^{0.5} \frac{1}{[(x-0.5)^2 + y^2]^{\frac{\alpha}{2}}} dx dy$$

Substituting formula (27) and (28) into formula (26), we have

$$\begin{aligned}
P_{out|A_l}^{(T)} & \leq [1 - \Upsilon^{\varphi_1}] + [1 - \Upsilon^{\varphi_2}] - [1 - \Upsilon^{\varphi_1}][1 - \Upsilon^{\varphi_2}] \\
& = 1 - \Upsilon^{\varphi_1 + \varphi_2}
\end{aligned} \quad (29)$$

3) $k < l \leq n$

In this case, the relay selection process is to select relay randomly in the candidate relay set \mathfrak{R} which consists of the relays with the first k large $\min(|h_{S,R_j}|^2, |h_{D,R_j}|^2)$ in the relay selection region.

Notice $P_{out|A_l}^{(T)}$ is determined as

$$\begin{aligned}
P_{out|A_l}^{(T)} & = P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) + P\left(O_{R_{j^*} \rightarrow D}^{(T)} \middle| A_l\right) \\
& \quad - P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) \cdot P\left(O_{R_{j^*} \rightarrow D}^{(T)} \middle| A_l\right)
\end{aligned} \quad (30)$$

Let the random variable $H = \min(|h_{S,R_{j^*}}|^2, |h_{D,R_{j^*}}|^2)$ and from Appendix C, the distribution function of H is

$$F_H(x) = \begin{cases} \frac{1}{k} \sum_{j=1}^k \left[\sum_{i=l-j+1}^l \binom{l}{i} [1 - e^{-2x}]^i [e^{-2x}]^{l-i} \right] & x > 0 \\ 0 & x \leq 0 \end{cases} \quad (31)$$

Based on the definition of transmission outage probability, employing the similar method above, we have

$$\begin{aligned}
& P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) \\
& \leq P\left(\frac{|h_{S,R_{j^*}}|^2 (0.5+r)^{-\alpha}}{\tau(n-1)(1-e^{-\tau})\varphi_1} \leq \gamma_R \middle| A_l\right) \\
& \leq P\left(H \leq \frac{\gamma_R \tau (n-1)(1-e^{-\tau})\varphi_1}{(0.5+r)^{-\alpha}} \middle| A_l\right)
\end{aligned}$$

From formula (31), we can get

$$\begin{aligned}
& P\left(O_{S \rightarrow R_{j^*}}^{(T)} \middle| A_l\right) \\
& \leq \frac{1}{k} \sum_{j=1}^k \left[\sum_{i=l-j+1}^l \binom{l}{i} (1 - \Upsilon^{2\varphi_1})^i \cdot (\Upsilon^{2\varphi_1})^{l-i} \right] \\
& = \frac{1}{k} \sum_{j=1}^k \left[1 - \sum_{i=0}^{l-j} \frac{\binom{l}{i}}{\binom{l-j}{i}} \binom{l-j}{i} (1 - \Upsilon^{2\varphi_1})^i \cdot (\Upsilon^{2\varphi_1})^{l-j-i} (\Upsilon^{2\varphi_1})^j \right] \\
& \leq \frac{1}{k} \sum_{j=1}^k \left[1 - (\Upsilon^{2\varphi_1})^j \right] \\
& = 1 - \frac{1}{k} \sum_{j=1}^k (\Upsilon^{2\varphi_1})^j \\
& = 1 - \frac{\Upsilon^{2\varphi_1} (1 - \Upsilon^{2k\varphi_1})}{k (1 - \Upsilon^{2\varphi_1})}
\end{aligned} \quad (32)$$

Employing the same method, we can get

$$P\left(O_{R_{j^*} \rightarrow D}^{(T)} \middle| A_l\right) \leq 1 - \frac{\Upsilon^{2\varphi_2} (1 - \Upsilon^{2k\varphi_2})}{k (1 - \Upsilon^{2\varphi_2})} \quad (33)$$

Substituting formula (32) and (33) into formula (30), we have

$$P_{out|A_l}^{(T)} \leq 1 - \frac{\Upsilon^{2(\varphi_1 + \varphi_2)} (1 - \Upsilon^{2k\varphi_1}) (1 - \Upsilon^{2k\varphi_2})}{k^2 (1 - \Upsilon^{2\varphi_1}) (1 - \Upsilon^{2\varphi_2})} \quad (34)$$

Substituting formula (24), (25), (29) and (34) into formula (23), we have

$$\begin{aligned}
P_{out}^{(T)} &= \sum_{l=0}^n P_{out|A_l}^{(T)} \cdot P(A_l) \\
&= P_{out|A_0}^{(T)} \cdot P(A_0) + \sum_{l=1}^k P_{out|A_l}^{(T)} \cdot P(A_l) \\
&\quad + \sum_{l=k+1}^n P_{out|A_l}^{(T)} \cdot P(A_l) \\
&\leq 1 \cdot (1 - \pi r^2)^n \\
&\quad + (1 - \Upsilon^{\varphi_1 + \varphi_2}) \sum_{l=1}^k \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} \\
&\quad + \left[1 - \frac{\Upsilon^{2(\varphi_1 + \varphi_2)} (1 - \Upsilon^{2k\varphi_1}) (1 - \Upsilon^{2k\varphi_2})}{k^2 (1 - \Upsilon^{2\varphi_1}) (1 - \Upsilon^{2\varphi_2})} \right] \\
&\quad \sum_{l=k+1}^n \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} \\
&\leq 1 - \Upsilon^{\varphi_1 + \varphi_2} \sum_{l=1}^k \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} \\
&\quad - \frac{\Upsilon^{2(\varphi_1 + \varphi_2)} (1 - \Upsilon^{2k\varphi_1}) (1 - \Upsilon^{2k\varphi_2})}{k^2 (1 - \Upsilon^{2\varphi_1}) (1 - \Upsilon^{2\varphi_2})} \\
&\quad \sum_{l=k+1}^n \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} \\
&\leq 1 - \Upsilon^{\varphi_1 + \varphi_2} \sum_{l=1}^k \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l} \\
&\quad - \frac{\Upsilon^{2(\varphi_1 + \varphi_2)}}{k^2} \sum_{l=k+1}^n \binom{n}{l} (\pi r^2)^l (1 - \pi r^2)^{n-l}
\end{aligned}$$

According to the definition of secrecy outage probability, we know that

$$P(O_{S \rightarrow R_{j^*}}^{(S)}) = P\left(\bigcup_{i=1}^m \{C_{S,E_i} \geq \gamma_E\}\right)$$

Thus, we have

$$P(O_{S \rightarrow R_{j^*}}^{(S)}) \leq \sum_{i=1}^m P(C_{S,E_i} \geq \gamma_E) \quad (35)$$

Based on the definition of d_0 , we denote by $G_1^{(i)}$ the event that the distance between E_i and the source is less than d_0 , and denote by $G_2^{(i)}$ the event that distance between E_i and the source is larger than or equal to d_0 . We have

$$\begin{aligned}
P(C_{S,E_i} \geq \gamma_E) &= P\left(C_{S,E_i} \geq \gamma_E \middle| G_1^{(i)}\right) P(G_1^{(i)}) \\
&\quad + P\left(C_{S,E_i} \geq \gamma_E \middle| G_2^{(i)}\right) P(G_2^{(i)}) \\
&\leq 1 \cdot \frac{1}{2} \pi d_0^2 \\
&\quad + P\left(\frac{\frac{|h_{S,E_i}|^2}{d_{S,E_i}^\alpha}}{\sum_{R_j \in \mathcal{R}_1} \frac{|h_{R_j,E_i}|^2}{d_{R_j,E_i}^\alpha}} \geq \gamma_E \middle| G_2^{(i)}\right) \left(1 - \frac{1}{2} \pi d_0^2\right)
\end{aligned}$$

of which

$$\begin{aligned}
P\left(\frac{\frac{|h_{S,E_i}|^2}{d_{S,E_i}^\alpha}}{\sum_{R_j \in \mathcal{R}_1} \frac{|h_{R_j,E_i}|^2}{d_{R_j,E_i}^\alpha}} \geq \gamma_E \middle| G_2^{(i)}\right) \\
\leq P\left(\frac{|h_{S,E_i}|^2 d_0^{-\alpha}}{\Gamma \int_0^1 \int_0^1 \frac{1}{[(x-x_{E_i})^2 + (y-y_{E_i})^2]^{\frac{\alpha}{2}}} dx dy} \geq \gamma_E \middle| G_2^{(i)}\right)
\end{aligned}$$

where (x_{E_i}, y_{E_i}) is the coordinate of the eavesdropper E_i . Γ is the sum of $(n-1)(1-e^{-\tau})$ independent exponential random variables.

From Fig 2 we know that the strongest interference at eavesdropper E_i happens when E_i is located in the point $(0,0)$, while the smallest interference at E_i happens it is located at four corners of the network region. By considering the smallest interference at eavesdroppers, we then have

$$\begin{aligned}
P(C_{S,E_i} \geq \gamma_E \middle| G_2^{(i)}) \\
\leq P\left(\frac{|h_{S,E_i}|^2 d_0^{-\alpha}}{\Gamma \psi} \geq \gamma_E\right) \\
= P(|h_{S,E_i}|^2 \geq \Gamma \gamma_E \cdot \psi \cdot d_0^\alpha)
\end{aligned}$$

here

$$\psi = \int_{-0.5}^{0.5} \int_{-0.5}^{0.5} \frac{1}{[(x-0.5)^2 + (y-0.5)^2]^{\frac{\alpha}{2}}} dx dy$$

Based on the Markov inequality,

$$\begin{aligned}
P(C_{S,E_i} \geq \gamma_E \middle| G_2^{(i)}) \\
\leq E_\Gamma \left[e^{-\Gamma \gamma_E \psi d_0^\alpha} \right] \\
= \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})}
\end{aligned}$$

Then, we have

$$\begin{aligned} P(C_{S,E_i} \geq \gamma_E) \\ \leq \frac{1}{2}\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left(1 - \frac{1}{2}\pi d_0^2 \right) \end{aligned} \quad (36)$$

Employee the same method, we have

$$\begin{aligned} P(C_{R_{j^*},E_i} \geq \gamma_E) \\ \leq \pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \end{aligned} \quad (37)$$

Notice that

$$\begin{aligned} & \frac{1}{2}\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \left(1 - \frac{1}{2}\pi d_0^2 \right) \\ &= \pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \\ & \quad - \frac{1}{2}\pi d_0^2 \left[1 - \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} \right] \\ &\leq \pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \end{aligned} \quad (38)$$

From formula (36), (37) and (38), we can get

$$\begin{aligned} P(O_{S \rightarrow R_{j^*}}^{(S)}) &\leq P(O_{R_{j^*} \rightarrow D}^{(S)}) \\ &\leq m \left[\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \right] \end{aligned} \quad (39)$$

Substituting formula (39) into formula (2), we have

$$\begin{aligned} P_{out}^{(S)} &\leq \\ & 2m \left[\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \right] \\ & - \left[m \left(\pi d_0^2 + \left(\frac{1}{1 + \gamma_E \psi d_0^\alpha} \right)^{(n-1)(1-e^{-\tau})} (1 - \pi d_0^2) \right) \right]^2 \end{aligned} \quad (40)$$

APPENDIX C

THE DISTRIBUTION FUNCTION AND PROBABILITY DENSITY OF $H = \min(|h_{S,R_{j^*}}|^2, |h_{D,R_{j^*}}|^2)$

Let the random variable $H = \min(|h_{S,R_{j^*}}|^2, |h_{D,R_{j^*}}|^2)$. The node R_{j^*} is randomly selected from the relay selection set consisting of system nodes with the first k large $\min(|h_{S,R_j}|^2, |h_{D,R_j}|^2)$, $j = 1, 2, \dots, n$. The distribution function and probability density of H is given by

$$F_H(x) = \begin{cases} \frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1 - e^{-2x}]^i [e^{-2x}]^{n-i} \right] & x > 0 \\ 0 & x \leq 0 \end{cases}$$

and

$$f_H(x) = \begin{cases} \frac{1}{k} \sum_{j=1}^k \left[\frac{n!}{(j-1)!(n-j)!} [1 - e^{-2x}]^{n-j} [e^{-2x}]^{j-1} [2e^{-2x}] \right] & x > 0 \\ 0 & x \leq 0 \end{cases}$$

Proof:

Because the random variable $H = \min(|h_{S,R_{j^*}}|^2, |h_{D,R_{j^*}}|^2)$ is the random selection relay from the first k large random variable $\min(|h_{S,R_j}|^2, |h_{D,R_j}|^2)$, $j = 1, 2, \dots, n$. From Appendix D,

$$F_H(x) = \frac{1}{k} \sum_{j=1}^k F_{H_j^l}(x)$$

$$f_H(x) = \frac{1}{k} \sum_{j=1}^k f_{H_j^l}(x)$$

According to Appendix E, we have

$$F_H(x) = \begin{cases} \frac{1}{k} \sum_{j=1}^k \left[\sum_{i=n-j+1}^n \binom{n}{i} [1 - e^{-2x}]^i [e^{-2x}]^{n-i} \right] & x > 0 \\ 0 & x \leq 0 \end{cases}$$

and

$$f_H(x) = \begin{cases} \frac{1}{k} \sum_{j=1}^k \left[\frac{n!}{(j-1)!(n-j)!} [1 - e^{-2x}]^{n-j} [e^{-2x}]^{j-1} [2e^{-2x}] \right] & x > 0 \\ 0 & x \leq 0 \end{cases}$$

■

APPENDIX D

THE RANDOMLY SELECTED VARIABLE FROM THE RANDOM VARIABLE SET

Let X_1, \dots, X_n be continuous random variables, with density $f_{X_1}(x), \dots, f_{X_n}(x)$ and distribution function $F_{X_1}(x), \dots, F_{X_n}(x)$. The random variable, indexed by Y , is selected randomly from X_1, \dots, X_n . The distribution function and probability density of Y is given by

$$F_Y(y) = \frac{1}{n} \sum_{i=1}^n F_{X_i}(y)$$

$$f_Y(y) = \frac{1}{n} \sum_{i=1}^n f_{X_i}(y)$$

Proof:

We assume the s -th random variable is selected as Y , $P(s = i) = \frac{1}{n}$, $i = 1, \dots, n$. Then we have

$$\begin{aligned} F_Y(y) &= P(Y \leq y) \\ &= \sum_{i=1}^n P(X_s \leq y | s = i) P(s = i) \\ &= \sum_{i=1}^n \frac{1}{n} P(X_s \leq y | s = i) \\ &= \sum_{i=1}^n \frac{1}{n} P(X_i \leq y) \\ &= \frac{1}{n} \sum_{i=1}^n F_{X_i}(y) \end{aligned}$$

$$\begin{aligned} f_Y(y) &= F'_Y(y) \\ &= \frac{1}{n} \sum_{i=1}^n F'_{X_i}(y) \\ &= \frac{1}{n} \sum_{i=1}^n f_{X_i}(y) \end{aligned}$$

■

APPENDIX E

THE DISTRIBUTION FUNCTION AND PROBABILITY DENSITY OF THE k -TH LARGEST RANDOM VARIABLE

The $|h_{A,B}|^2$ is path-loss between any node A and B with the Rayleigh fading, and is exponentially distributed with $E[|h_{A,B}|^2] = 1$. The $\min(|h_{S,R_j}|^2, |h_{D,R_j}|^2)$, $j = 1, 2, \dots, n$, are n random variables in which the j -th largest random variable is denoted by H_j^l . The distribution function and probability density of the random variable H_j^l , $j = 1, 2, \dots, n$, are given by

$$\begin{aligned} F_{H_j^l}(x) &= \begin{cases} \sum_{i=n-j+1}^n \binom{n}{i} [1 - e^{-2x}]^i [e^{-2x}]^{n-i} & x > 0 \\ 0 & x \leq 0 \end{cases} \\ f_{H_j^l}(x) &= \begin{cases} \frac{n!}{(j-1)!(n-j)!} \cdot [1 - e^{-2x}]^{n-j} [e^{-2x}]^{j-1} [2e^{-2x}] & x > 0 \\ 0 & x \leq 0 \end{cases} \end{aligned}$$

Proof:

Because the $|h_{A,B}|^2$ is exponentially distributed with $E[|h_{A,B}|^2] = 1$ between any node A and B , according to order statistics in [32], we can get the distribution function of the $\min(|h_{S,R_j}|^2, |h_{D,R_j}|^2)$ for each relay R_j , $j = 1, 2, \dots, n$, indexed by H_j , as following,

$$f_{H_j}(x) = \begin{cases} 2e^{-2x} & x > 0 \\ 0 & x \leq 0 \end{cases}$$

$$F_{H_j}(x) = \begin{cases} 1 - e^{-2x} & x > 0 \\ 0 & x \leq 0 \end{cases}$$

According to order statistics in [32], The distribution function and probability density of the j -th smallest in H_j , $j = 1, 2, \dots, n$, indexed by H_j^s , are given by

$$\begin{aligned} F_{H_j^s}(x) &= \begin{cases} \sum_{i=j}^n \binom{n}{i} [1 - e^{-2x}]^i [e^{-2x}]^{n-i} & x > 0 \\ 0 & x \leq 0 \end{cases} \\ f_{H_j^s}(x) &= \begin{cases} \frac{n!}{(j-1)!(n-j)!} \cdot [1 - e^{-2x}]^{j-1} [e^{-2x}]^{n-j} [2e^{-2x}] & x > 0 \\ 0 & x \leq 0 \end{cases} \end{aligned}$$

Since the j -th largest, indexed by H_j^l , is equal to the $(n - j + 1)$ -th smallest in H_j , $j = 1, 2, \dots, n$, we should have

$$\begin{aligned} F_{H_j^l}(x) &= F_{H_{n-j+1}^s}(x) \\ &= \begin{cases} \sum_{i=n-j+1}^n \binom{n}{i} [1 - e^{-2x}]^i [e^{-2x}]^{n-i} & x > 0 \\ 0 & x \leq 0 \end{cases} \end{aligned}$$

$$\begin{aligned} f_{H_j^l}(x) &= f_{H_{n-j+1}^s}(x) \\ &= \begin{cases} \frac{n!}{(j-1)!(n-j)!} \cdot [1 - e^{-2x}]^{n-j} [e^{-2x}]^{j-1} [2e^{-2x}] & x > 0 \\ 0 & x \leq 0 \end{cases} \end{aligned}$$

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